

Dark Axion Portal

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The dark photon and the axion (or axion-like particle) are among the popular light particles of the hidden sector. Each of them has been actively searched for through the couplings called the vector portal and the axion portal. We introduce a new portal connecting the dark photon and the axion (axion-photon-dark photon, axion-dark photon-dark photon), which emerges in the presence of the two particles. This dark axion portal is genuinely new couplings, not just from a product of the vector portal and the axion portal, because of the internal structure of these couplings. We present a simple model that realizes the dark axion portal and discuss why it warrants rich phenomenology.

Introduction

Despite of the huge success of the standard model (SM), there are reasons to believe that our physical world is composed of more particles. They include those that do not couple to the SM particles in a vivid way (e.g., dark matter), often called the hidden sector particles.

Because of the small couplings to the SM particles, a hidden sector particle can be much lighter than the electroweak scale. The concept of the *portals* has helped understanding the possible mixing of the hidden sector with the SM and how to search for them. Known portals include

- (i) Vector portal: $B_{\mu\nu}Z'^{\mu\nu}$,
- (ii) Axion portal: $(a/f_a)F_{\mu\nu}\tilde{F}^{\mu\nu}, \dots$,
- (iii) Higgs portal: $|S|^2 H^\dagger H, \dots$,
- (iv) Neutrino portal: LHN .

For a review on the relevant physics of these portals, see Ref. [1]. The relic dark matter (DM) can be either a portal particle or just couples to a portal particle via a hidden interaction. For instance, it may couple to a new vector boson [2] or an axion-like particle (ALP) [3].

There are natural setups that can combine the portals. For example, the vector portal and Higgs portals can coexist as a Higgs singlet can provide a mass to a new vector boson (or dark photon). It then suggests a new search scheme of the hidden sector particles, for instance, a rare Higgs decay, $H \rightarrow Z'Z' \rightarrow 4\text{-leptons}$ where the first decay relies on the Higgs portal and the second decay relies on the vector portal [4]. This is basically based on the product of the two portals. (For more recent studies on this and the related topics, see Refs. [5–9].)

In this paper, we introduce and investigate a new portal that emerges when a dark photon and an axion coexist. New vertices (axion-photon-dark photon, axion-dark photon-dark photon) materialize through the triangle diagrams (see Fig. 1). Intriguingly, the new vertices are not just from a product of two individual portals, but rather genuinely new couplings. It is because of the new colored fermions that are charged under both the gauged $U(1)_{\text{Dark}}$ and the global $U(1)_{PQ}$. Therefore, the dark

photon can be attached to the triangle loop directly, not necessarily through the mixing of the vector portal. Such new colored fermions are required to construct the KSVZ type axion models [10, 11]. We shall call the new portal that connects the dark photon and the axion physics, the “dark axion” portal.

The dark photon and axion are widely studied light hypothetical particles with active experimental searches around the world. The typical search schemes are based on the portal interaction of each particle, yet it might be incomplete in the presence of both particles. Nature of the dark axion portal illustrates that the implications including the best search schemes could be beyond the native expectations.

Here is the outline for the rest of this paper. After we describe the dark axion portal terms, we introduce a simple model that realizes the new portal. Among the many possible implications, we provide one by presenting a new production mechanism for the dark photon DM in the early universe using the dark axion portal.

Although we choose a QCD axion that addresses the strong CP problem for the definiteness, many discussions here can be extended for the ALP. Comprehensive studies including the ALP case will be given elsewhere [12].

Dark Axion Portal

After a dark photon (γ' or Z') gets a small mass, the vector portal well below the electroweak scale is given by

$$\mathcal{L}_{\text{vector portal}} = \frac{\varepsilon}{2} F_{\mu\nu} Z'^{\mu\nu} \quad (1)$$

where $F_{\mu\nu}$ and $Z'_{\mu\nu}$ are the field strengths of the photon and dark photon. ε is the kinetic mixing parameter between the two $U(1)$ gauge symmetries [13], which is experimentally constrained to be very small ($\varepsilon^2 \ll 1$) [1]. The dark photon has been motivated from various dark matter related physics (such as the positron excess [2]) and other physics (such as the $g_\mu - 2$ anomaly [17–19]).

It should be mentioned that the full description before the symmetry breaking should be as a kinetic mixing between the $U(1)_Y$ hypercharge and the $U(1)_{\text{Dark}}$ [14].

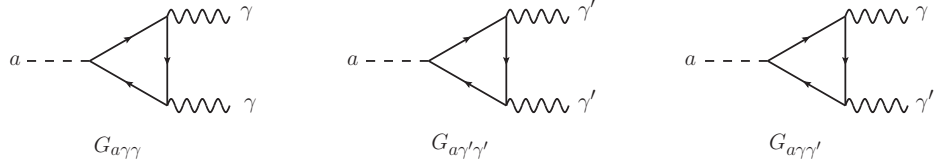


FIG. 1. Extended axion couplings. The latter two are the new couplings from the dark axion portals.

However, it is sufficient to consider only the $U(1)_{\text{QED}}$ and the $U(1)_{\text{Dark}}$ mixing as long as $m_{\gamma'}^2/m_Z^2 \ll 1$, which is why it is called the dark photon. We will take this approach in this paper, and postpone the generalization including a full description to a subsequent work [12].¹

The axion portal is given by

$$\mathcal{L}_{\text{axion portal}} = \frac{G_{agg}}{4} a G^{\mu\nu} \tilde{G}_{\mu\nu} + \frac{G_{a\gamma\gamma}}{4} a F^{\mu\nu} \tilde{F}_{\mu\nu} + \dots (2)$$

where $G_{\mu\nu}$ is the gluon field strength, tilde notation is for the dual, and a is the axion.

The global Peccei-Quinn symmetry $U(1)_{PQ}$ was introduced to solve the strong CP problem [20, 21], which predicts a pseudo-Nambu-Goldstone boson, axion after the symmetry breaking [22, 23]. In the invisible axion models [10, 11, 24, 25], the PQ symmetry is broken spontaneously at an energy scale much higher than the electroweak scale. The axion portal applies to the ALP too, which does not address the strong CP problem.

In the presence of the dark photon, an axion can couple to two photons, two dark photons as well as a photon and a dark photon. (See Fig. 1.) These interactions are given by the nonrenormalizable dark axion portal terms.

$$\mathcal{L}_{\text{dark axion portal}} = \frac{G_{a\gamma'\gamma'}}{4} a Z'_{\mu\nu} \tilde{Z}'^{\mu\nu} + \frac{G_{a\gamma\gamma'}}{2} a F_{\mu\nu} \tilde{Z}'^{\mu\nu} (3)$$

They are induced by the axion anomalous triangle couplings to (dark) photons as shown in Fig. 1. Note the fermions in the triangle loop can have both $U(1)_{PQ}$ and $U(1)_{\text{Dark}}$ charges as well as the electromagnetic charges, and the dark photon can couple to them directly.²³

Dark KSVZ Model

There are more than one way to realize the dark axion portal, but here we provide one of the simplest models based on the KSVZ type axion [10, 11], and we call it

“dark KSVZ” model. (Other models including the ALP case will be studied elsewhere [12].)

We take the $U(1)_{\text{Dark}}$ gauge symmetry and the $U(1)_{PQ}$ global symmetry. We introduce only two Weyl fermions ψ and ψ^c , which are colored singlets. Note that our setup is free from the domain wall issue [28] since we have introduced only one flavor of the heavy quarks. They are vectorial under the gauge symmetries including the $U(1)_{\text{Dark}}$ so that the model is anomaly-free, yet chiral under the $U(1)_{PQ}$. We also introduce two Higgs singlets Φ_{PQ} and Φ_D whose CP-odd components become an axion and the dark photon longitudinal mode. Table I shows the new fields and their charge assignments in our model. All SM fields have zero charges under the $U(1)_{\text{Dark}}$ and $U(1)_{PQ}$. Yukawa terms for the exotic fermions are given by

$$\mathcal{L}_\psi = y_\psi \Phi_{PQ} \psi \psi^c + h.c., (4)$$

which dictates $PQ_\Phi = -(PQ_\psi + PQ_{\psi^c})$.

As Φ_{PQ} develops a vacuum expectation value (VEV), the $U(1)_{PQ}$ is spontaneously broken at a scale f_a (axion decay constant) given by $f_a^2 = PQ_\Phi^2 v_{PQ}^2$ with $\Phi_{PQ} = \frac{1}{\sqrt{2}}(S_{PQ} + v_{PQ})e^{iPQ_\Phi(a/f_a)}$. It gives a mass to the exotic fermions $m_\psi = \frac{y_\psi}{\sqrt{2}}v_{PQ}$. After the QCD phase transition, the axion mass is given by $m_a \simeq \frac{\sqrt{z}}{1+z} \frac{f_\pi}{f_a} m_\pi$, where $z = m_u/m_d \simeq 0.56$, and $m_\pi \simeq 135$ MeV and $f_\pi \simeq 92$ MeV are the mass and the decay constant of the pion, respectively. For the spontaneous breaking of $U(1)_{\text{Dark}}$, as Φ_D develops a VEV, $\langle \Phi_D \rangle = v_D/\sqrt{2}$, the dark photon acquires a mass given by $m_{\gamma'}^2 = e'^2 D_{\Phi_D}^2 v_D^2$.

We derive the axion portal and the dark axion portal terms at the leading order in ε as following.

$$G_{agg} = \frac{g_S^2}{8\pi^2} \frac{PQ_\Phi}{f_a} (5)$$

$$G_{a\gamma\gamma} = \frac{e^2}{8\pi^2} \frac{PQ_\Phi}{f_a} \left[2N_C Q_\psi^2 - \frac{2(4+z)}{3(1+z)} \right] (6)$$

$$G_{a\gamma\gamma'} \simeq \frac{ee'}{16\pi^2} \frac{PQ_\Phi}{f_a} [2N_C D_\psi Q_\psi] + \varepsilon G_{a\gamma\gamma} (7)$$

$$G_{a\gamma'\gamma'} \simeq \frac{e'^2}{8\pi^2} \frac{PQ_\Phi}{f_a} [2N_C D_\psi^2] + 2\varepsilon G_{a\gamma\gamma'} (8)$$

$N_C = 3$ is the color factor, g_S is the $SU(3)_C$ gauge coupling, and e' is the $U(1)_{\text{Dark}}$ gauge coupling, which can be as sizable as the SM gauge couplings. Note the PQ_Φ dependence is not real as it is cancelled by the same factor in f_a .

¹ One can also take a gauge symmetry which has a nonzero charges for the SM particles as well as the kinetic mixing [16].

² In the axion model with the mirror symmetry [26, 27], where the massless mirror photon is present, the axion-mirror photon-mirror photon coupling exists. In some sense, it corresponds to the $G_{a\gamma'\gamma'}$, but the $G_{a\gamma\gamma'}$ does not exist in this kind of models.

³ Strictly speaking, $G_{a\gamma'\gamma'}$ is not a traditional portal that connects the SM sector to the hidden sector. This portal rather connects the dark photon sector to the axion sector.

| Field | $SU(3)_C$ | $SU(2)_L$ | $U(1)_Y$ | $U(1)_{\text{Dark}}$ | $U(1)_{PQ}$ |
|-------------|-----------|-----------|-----------|----------------------|---------------|
| ψ | 3 | 1 | Q_ψ | D_ψ | PQ_ψ |
| ψ^c | $\bar{3}$ | 1 | $-Q_\psi$ | $-D_\psi$ | PQ_{ψ^c} |
| Φ_{PQ} | 1 | 1 | 0 | 0 | PQ_Φ |
| Φ_D | 1 | 1 | 0 | D_Φ | 0 |

TABLE I. New fields and charge assignments in our model. Q_ψ is the electromagnetic charge of the exotic fermion ψ .

These expressions clearly show that the dark axion portal couplings are not just from the product of two individual portals (e.g., $\varepsilon G_{a\gamma\gamma}$, which is greatly suppressed because $\varepsilon^2 \ll 1$), but they are rather new, relatively large couplings originating from the dark gauge symmetry. As a matter of fact, the new couplings $G_{a\gamma\gamma'}$, $G_{a\gamma'\gamma'}$ may be still sizable even when the vector portal and axion portal vanish ($\varepsilon \simeq 0$, $G_{a\gamma\gamma} \simeq 0$). The $G_{a\gamma\gamma'}$ would vanish if the new colored fermions do not carry electric charges ($Q_\psi = 0$), except for the vector portal (ε) induced part.⁴

Stability of the exotic colored fermion (ψ , ψ^c) is a generic issue of the KSVZ model. This unwanted challenge can be avoided in our model by an appropriate charge assignment for these particles. For example, for the choice of $PQ_\psi = 0$ and $Q_\psi = -1/3$, the $\Phi_D^\dagger \psi D^c$ term is allowed. Then the exotic fermion can decay into the SM down-type quark and the SM singlet scalar S_D , which can subsequently decay into the dark photon.

The Higgs portal can be also introduced in this model because of the existence of the Φ_{S_i} although we do not focus on that part in this paper.

Decays

The dark photon decay widths are given by following.

$$\Gamma(\gamma' \rightarrow e^+ e^-) = \frac{\varepsilon^2 e^2}{12\pi} m_{\gamma'} \left[1 - \frac{4m_e^2}{m_{\gamma'}^2} \right]^{1/2} \quad (9)$$

$$\Gamma(\gamma' \rightarrow \gamma a) = \frac{G_{a\gamma\gamma'}^2}{96\pi} m_{\gamma'}^3 \left[1 - \frac{m_a^2}{m_{\gamma'}^2} \right]^3 \quad (10)$$

This can be compared to the $\Gamma(\gamma' \rightarrow 3\gamma) \approx (5 \times 10^{-8}) \varepsilon^2 (e^2/4\pi^2)^4 (m_{\gamma'}^9/m_e^8)$ [29], which would be the dominant decay mode for a sub-MeV dark photon if there is no dark axion portal decay of $\gamma' \rightarrow \gamma a$.

The axion decay widths are given by

$$\Gamma(a \rightarrow \gamma\gamma) = \frac{G_{a\gamma\gamma}^2}{64\pi} m_a^3 \quad (11)$$

$$\Gamma(a \rightarrow \gamma\gamma') = \frac{G_{a\gamma\gamma'}^2}{32\pi} m_a^3 \left[1 - \frac{m_{\gamma'}^2}{m_a^2} \right]^3 \quad (12)$$

$$\Gamma(a \rightarrow \gamma'\gamma') = \frac{G_{a\gamma'\gamma'}^2}{64\pi} m_a^3 \left[1 - \frac{4m_{\gamma'}^2}{m_a^2} \right]^{3/2} \quad (13)$$

⁴ These couplings would change if there are more fermions, e.g. some exotic leptons, that can be in the triangles of Fig. 1.

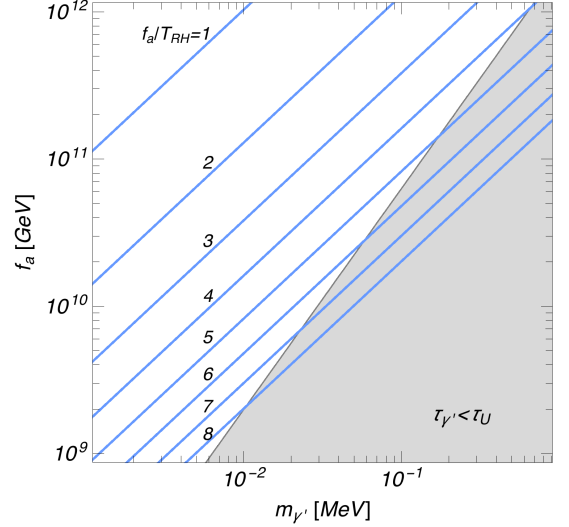


FIG. 2. On the blue lines, $\Omega_{\gamma'} h^2 = 0.12$ for the given f_a/T_{RH} values. We choose $e' = 0.1$, $D_\psi = 3$, $Q_\psi = -1/3$ for an illustration. For low f_a , the axion alone cannot explain the observed relic density, yet it can be accounted for with the γ' .

The G_{ae+e-} coupling is 2-loop suppressed in our model as it is a hadronic axion (KSVZ type).

Implications in the Cosmology

There may be plenty of applications of the dark axion portal, and here we illustrate one in the cosmology with the dark KSVZ model. We present a novel production mechanism of the dark photon DM candidate in the early universe using the dark axion portal, which can also address an issue of the axion DM relic density. Known production mechanism of the dark photon DM is very rare [32], although physics of the dark photon DM physics is widely investigated [33].

In the QCD axion model, the viable window of the f_a is given by $10^9 \text{ GeV} \lesssim f_a \lesssim 10^{12} \text{ GeV}$. The lower bound is from the SN1987A data, and the upper bound is from the relic density constraint ($\Omega_{\text{DM}} h^2 = 0.12$), which is obtained from the misalignment mechanism [34]. Below the 10^{11} GeV , the required relic density may not be explained by the axion DM alone. We take the dark photon as another DM candidate produced by the freeze-in mechanism [30, 31] through the dark axion portal. This additional dark matter can compensate for the required relic density.

For the definiteness, we take a negligible kinetic mixing ($\varepsilon \simeq 0$), and consider the dark photon of roughly keV scale. Then, the dominant decay channel of the dark photon is $\gamma' \rightarrow a\gamma$ provided by a dark axion portal.

The main process to connect the SM sector with the dark sector is gg , $\gamma\gamma \leftrightarrow \gamma'\gamma'$ mediated by the axion. Because of a large f_a , this reaction is feeble and cannot bring

γ' into the thermal bath. Then, the freeze-in mechanism ($gg, \gamma\gamma \rightarrow \gamma'\gamma'$) can work to produce the non-thermal γ' .

The Boltzmann equation for the γ' is given by

$$-SHT \frac{dY_{\gamma'}}{dT} = \gamma[n_{\gamma'}], \quad Y_{\gamma'} \equiv n_{\gamma'}/S, \quad (14)$$

where $\gamma[n_{\gamma'}]$ denotes the collision term, and we use $S = (2\pi^2/45)g_{*s}T^3$ (entropy density) and $H^2 = (\pi^2/90)g_{*p}T^4/M_{\text{Pl}}^2$ (Hubble parameter) with $M_{\text{Pl}} \simeq 2.4 \times 10^{18}$ GeV. In the following discussion, we take $g_{*s} = g_{*p} \equiv g_*$ as a constant value.

We take only the dominant gluon contribution, and the annihilation cross section is approximately given by $\sigma v \simeq 4G_{agg}^2 G_{a\gamma'\gamma'}^2 s$. We then obtain

$$\gamma[n_{\gamma'}] \simeq \frac{48}{\pi^4} G_{agg}^2 G_{a\gamma'\gamma'}^2 T^8, \quad (15)$$

where we neglect $m_{\gamma'}$, and thus, by integrating T from T_{RH} to 0, we end up with $Y_{\gamma'}^0 \equiv Y_{\gamma'}(T=0)$ as

$$Y_{\gamma'}^0 \simeq \frac{1080\sqrt{10}}{\pi^7 g_*^{3/2}} G_{agg}^2 G_{a\gamma'\gamma'}^2 M_{\text{Pl}} T_{\text{RH}}^3 \quad (16)$$

where T_{RH} is the reheating temperature. Then, we obtain

$$\begin{aligned} \Omega_{\gamma'} h^2 &= S_0 m_{\gamma'} Y_{\gamma'}^0 (\rho_c/h^2)^{-1} \\ &\simeq 0.1 \times g_D^4 \left[\frac{10^2}{g_*} \right]^{\frac{3}{2}} \left[\frac{m_{\gamma'}}{10 \text{ keV}} \right] \left[\frac{5 T_{\text{RH}}}{f_a} \right]^3 \left[\frac{10^{10}}{f_a/\text{GeV}} \right] \end{aligned} \quad (17)$$

where $\rho_c = 1.05368 \times 10^{-5} h^2 \text{ GeV cm}^{-3}$ and $S_0 = 2889.2 \text{ cm}^{-3}$ are the critical density and the entropy density at the present time. We define $g_D \equiv (e' D_\psi/0.3)$.

The viable parameter region is shown in Fig. 2 for a choice of parameter values. In the gray region, the lifetime of the dark photon ($\tau_{\gamma'}$) is shorter than the age of the universe $\tau_U \sim 13.7 \times 10^9$ years, where the main decay mode is $\gamma' \rightarrow a\gamma$. One can take low T_{RH} to reduce the dark photon relic density, and can always find the total relic density of the axion and dark photon system that can explain the observed relic density.

It should be noted that there is an upper limit on T_{RH} for the freeze-in DM production to work since at $T = T_{\text{RH}}$ the DM annihilation takes place most frequently and the it might be thermalized if T_{RH} is sufficiently high. This upper bound can be obtained by imposing $r_{\gamma'} < H$ at $T = T_{\text{RH}}$, where the reaction rate is $r_{\gamma'} \equiv \gamma[n_{\gamma'}]/n_{\gamma'}^{\text{eq}}$ with $n_{\gamma'}^{\text{eq}} \simeq (3\zeta(3)/\pi^2)T^3$. Then, the upper bound becomes

$$T_{\text{RH}} \lesssim (10^{10} \text{ GeV}) \times g_D^{-\frac{4}{3}} \left[\frac{g_*}{10^2} \right]^{\frac{1}{6}} \left[\frac{f_a/\text{GeV}}{10^{10}} \right]^{\frac{4}{3}} \quad (18)$$

above which γ' may be thermalized, leading to the overproduction.⁵ Note that for lower reheating temperatures,

the observed DM abundance requires rather a small f_a , which may conflict with the constraint on the γ' lifetime. This tension can be, however, easily evaded by taking $Q_\psi = 0$ (electrically neutral exotic colored fermions)⁶ so that the decay through $\gamma' \rightarrow a\gamma$ is forbidden if we keep $\varepsilon \simeq 0$.

Summary and Outlook

Many researches about the hidden sector have been performed in the framework of the portals. Among them are the vector portal and the axion portal, which are useful to understand the possible couplings and determine the best search methods for the dark photon and axion (or ALP), respectively. Each of them has been extensively studied and experimentally searched for.

We investigated the physics and phenomenological consequences when both new particles exist together. A new portal connecting the dark photon and axion (axion-photon-dark photon, axion-dark photon-dark photon) emerges. The new couplings can be much stronger than the simple product of the vector portal and axion portal couplings. Typical search schemes could be invalidated in some cases, and new search schemes based on this dark axion portal could be more important.

We exhibited the dark axion portal by constructing a new model based on the KSVZ axion model. Because of the nature of the QCD axion, which has an extremely tiny mass and feeble couplings, the relevant implications are in the cosmology and/or astroparticle physics area. We illustrated the usefulness of the new portal with an example of the relic density issue of the axion dark matter using the $gg/\gamma\gamma - a - \gamma'\gamma'$ channels. The dark axion portal provides a novel mechanism for the dark photon production, and a sufficiently light dark photon can be a dark matter candidate that can compensate the deficit of the relic density of the axion dark matter when the axion decay constant is low. Various channels of production and decay for the axion/dark photon are allowed through the dark axion portal, and the traditional implications should be revisited in this new picture.

The dark axion portal is not particular for the QCD axion, but can be applied to the ALP whose mass and couplings can be large enough so that many lab experiments such as rare meson decays or beam dump experiments are relevant. Various model buildings realizing the dark axion portal and rich phenomenology are warranted.⁷ As all other portals have done in the past, the introduction of a new portal will open great opportunities for many subsequent studies.

⁶ Exotic colored fermions might be stable for this charge assignment, but their production would be little as the reheating temperature is lower than their mass scale, f_a .

⁷ Around the time we were completing our study, there were some studies to combine the axion and dark photon together [27, 36].

⁵ This may still be consistent with the condition $T_{\text{RH}} \gtrsim 10^9$ GeV, which is required by the thermal leptogenesis [35].

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 - [36] For example, see H. J. Kim and K. Choi's presentations (KIAS, November 27-28, 2016) where their plan to use a new light gauge boson to reduce the entropy in their future study of the relaxation in the early universe was mentioned.